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APPLICATIONS OF MICROWAVES TO REMOTE SENSING OF TERRAIN

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16. Abstract

A survey and study has been conducted to define the role that microwaves may play in the measurement of a variety of terrain-related parameters. The survey consisted of discussions with many users and researchers in the field of remote sensing. In addition, a Survey Questionnaire was prepared and replies were solicited from these and other users and researchers.

The results of the survey, and associated bibliography, were studied and conclusions were drawn as to the usefulness of radiometric systems for remote sensing of terrain.

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Section 1

INTRODUCTION

The purpose of the work described in this report was to conduct a survey and perform a study, to define the role that microwaves may play in the measurement of terrain-related parameters such as soil moisture, crop and vegetation identification, determination of crop growth stage and similar items of interest to users of remotely sensed data. In addition, a study was required on the advantages and disadvantages of microwaves over other remote sensing techniques, both airborne and spaceborne.

The survey consisted of in-depth discussions with many users of remotely sensed data and researchers in this field; attendance at the Ninth International Symposium on Remote Sensing of Environment; a visit to the Laboratory for Applications of Remote Sensing at Purdue University; and solicitation of replies to a variety of questions listed in a detailed Survey Questionnaire.

The information accumulated, as a result of the survey, was summarized and analyzed. In addition, technical material furnished by many of the users and researchers was studied. This information is listed in the References and Bibliography. The results of the survey are presented in Section 3; analyses of the results appear in Sections 4 and 5. Section 6 furnishes a list of references and Section 7 furnishes a bibliography of technical material provided or referenced by users and researchers.

It is clear that, in a survey and study of such broad scope, it would have been relatively easy to assign a man-year of effort to the entire effort. However, constraints imposed by the project, of which the survey is a minor part, restricted this work to less than 1.5 man-months. Despite the brevity of the effort, it is felt that the results are representative and the analyses, conducted thereon, are valid.

The results of the survey and study show that microwaves can play an important role in remote sensing, partly due to their relative immunity to the effects of weather, partly to their unique detection capabilities (water salinity and soil moisture) and partly to their ability to "see" through foliage and limited thicknesses of soil. Although it may be difficult to achieve adequate spatial resolution with low frequency microwave radiometric sensors, from earth satellites, focused side-looking radar (SLR) can furnish a resolution of, at least, 15 meters from such vehicles. Of course, SLR cannot measure water salinity nor water temperature.

Based on the results of this work, it is clear that microwaves can play an important role in remote sensing of terrain, from aircraft and spacecraft. Accordingly, it is recommended that plans be initiated at an early date for airborne and spaceborne microwave systems. At the same time, development of the related data processing and automated data analysis techniques should be accelerated. It is felt that proper implementation of this work will be of considerable value to the remote sensing field.

Section 2

TERRAIN SURVEY APPROACH

2.1 INTRODUCTION

In certain respects, this survey has been viewed as an extension of the survey conducted in connection with the study performed by Porter and Florance [1]. In that work, a representative variety of microwave radiometric data were generated and collected for use in computing brightness temperatures radiated by various terrestrial materials and phenomena, under a range of atmospheric conditions. The detectability of the materials and phenomena was, then, computed at seven (7) microwave and millimeter-wave frequencies, with state-of-the-art radiometric systems operating with specified antenna apertures.

Time has not permitted a similarly ambitious study in connection with this survey; the above work occupied a period of ten (10) months, whereas the time devoted to this survey has been just two (2) months. Of course, the objectives of this study are somewhat different from the referenced work, in that extensive data manipulations and analyses were not required. In addition, an exhaustive evaluation of the state-of-the-art of microwave radiometric systems and space-type antennas was not essential. However, a considerable amount of useful information has been accumulated to permit a valid assessment of the role that microwaves may play in the measurement of various terrain-related parameters. This has included results from ground-based, airborne and space-borne radiometric observations of such items as soils, vegetation, fresh water, snow, ice and oil spills in ocean water. Some of the equipments and analytical techniques, employed in these observations, have been quite sophisticated. Accordingly, the results obtained have provided a firm basis for this study.

2.2 SURVEY APPROACH DETAILS

Due to the short period of time available for the survey, it was decided to obtain the requisite information in the following manner:

1. Attendance at the Ninth International Symposium on Remote Sensing of Environment, held April 15-19th, 1974 at the University of Michigan.

2. Meetings with researchers in the remote sensing field and with users of remotely sensed data.

and 3. Solicitation of replies to a comprehensive questionnaire from individuals engaged in remote sensing activities and from users of remotely sensed data.

2.2.1 COMMENTS ON THE SYMPOSIUM

A total of thirteen (13) papers dealt with microwave radiometry. One other, to be written by a Russian author, was not presented. Eleven (11) papers, dealing with radar, were presented. Most of these involved side-looking radar. An additional paper, to be written by a Russian author, was not presented. Reference [2] provides summaries of papers given at the Symposium.

Two interesting papers [3, 4] dealing with microwave radiometry, have been obtained in preprint form. The first-mentioned paper describes ground-based radiometric observations at 1.4 and 10.7 GHz. The L-band radiometer data shows a satisfactory response to soil moisture through low density vegetation, for vertical polarization. In addition, surface roughness appears to have little effect on soil moisture response for this polarization.

The second-mentioned paper presents airborne imagery of agricultural areas, obtained with a 35 GHz scanning radiometer, during winter, spring and summer conditions. The data show that field patterns, ponds, lakes, roads, forested areas and buildings are detectable through approximately 0.5-meter snow depths. In addition, these features and buildings were imaged through a cloud layer 1,500 feet thick. This is rather significant, at this frequency, and indicates the superiority of microwave sensors over those in the visible and infrared regions, where atmospheric effects are concerned.

Most of the non-microwave papers, presented at the Symposium, dealt with data obtained by the ERTS-1 Multi-Spectral Scanner (MSS). It was clear from these that ERTS is performing a valuable function in the measurement of terrain-related parameters, notwithstanding the sensors' inability to penetrate cloud cover and collect information on the dark side of the earth, and the satellite's infrequent scan repetition (once every 18 days). Although the MSS sensors are limited to operation over the daylight side of the earth, the Data Collection Platforms permit reception of telemetered data under, both, daylight and nighttime conditions. These devices tend to mitigate the shortcomings of the MSS sensors, where cloudy and nighttime conditions are concerned.

2.2.2 MEETINGS WITH RESEARCHERS AND USERS IN REMOTE SENSING FIELD

Several important meetings were held with researchers in the remote sensing field and with users of remotely sensed data, to obtain information for the survey. These are listed below:

1. L.F. Silva, D.A. Landgrebe, R.M. Hoffer, F. Schultz, B. Robinson and V. Vanderbilt, Laboratory for Applications of Remote Sensing, Purdue University, West Lafayette, Indiana.
2. R.H. Miller, U.S. Dept. of Agriculture, Washington, DC.
3. W. Fischer, D. Carter and C. Robinove, EROS Program, U.S. Geological Survey, Reston, Virginia.
4. G.B. Torbert and J.M. Linne, Bureau of Land Management, Dept. of the Interior, Washington, DC.
5. J.D. Koutsandreas, Environmental Protection Agency, Washington, DC.
6. E.P. McLain, A.E. Strong, D.R. Wiesnet and J.W. Sherman, III, National Environmental Satellite Service, National Oceanic and Atmospheric Administration, Hillcrest Heights, Maryland.
7. T.J. Schmugge, NASA Goddard Space Flight Center, Greenbelt, Maryland.

The results of the above personal contacts are given in Section 3.

2.2.3 REMOTE SENSING QUESTIONNAIRE

To facilitate collection of information for the terrain survey, a comprehensive questionnaire was prepared, reproduced and forwarded to twenty-four (24) researchers and users in the field of remote sensing. The questionnaire consists of three (3) pages and cites the purpose of the survey, followed by fifteen (15) individual questions to be answered by the addressee. The questionnaire is reproduced on the following pages. A total of fifteen (15) replies were received from this solicitation. These are considered to be representative of the remote sensing field. Many replies include extensive bibliographies; a few respondents furnished copies of recent papers.

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TECHNICAL SURVEY

NASA - Langley Contract NAS 1-13126

MICROWAVE RADIOMETRIC SENSING OF TERRAIN

PURPOSE OF SURVEY

1. To define the role that airborne and spaceborne microwave radiometry may play in the measurement of terrain-related parameters.
2. To determine the advantages and disadvantages of microwave radiometry over other remote sensing techniques (space and airborne).

The prime terrain-related parameters, to be covered in the survey, are as follows:

1. Soil identification
2. Soil temperature
3. Soil and snow moisture, with distribution
4. Soil moisture for landslide potential
5. Snow depth and density
6. Discrimination between crops, forests and other vegetation
7. Discrimination between crops
8. Discrimination between different types of trees
9. Crop and forest growth stage
10. Crop diseases
11. Forest diseases - for example, defoliation due to gypsy moth infestation
12. Crop and forest acreage
13. Crop and forest moisture
14. Detection of forest fires
15. Assessment of burned and clear cut areas
16. Flood boundaries
17. Water pollution - thermal and chemical
18. Fresh water ice
19. Beach erosion
20. Geological features - fault lines, volcanic activity, lava flows, and extent of strip mining
21. Hydrogeological - glacial, snow and ice
22. Land use - crop and truck farming
    - housing
    - transportation

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Date:____________1974

MICROWAVE RADIOMETRIC SENSING OF TERRAIN

SURVEY QUESTIONNAIRE

1. User name and address____________________

2. Materials and phenomena of interest____________________

3. Why is remotely sensed data important to you?____________________

4. How important is remote sensing to you? Please explain____________________

5. What is the required data accuracy? (%, ^{o}K, Position in appropriate units)_____

6. What order of spatial resolution is required for your purposes? (Sq. meters, sq. ft., acres, sq. miles, etc.)____________________

7. What types of correlative data are considered important for your purposes?_____

8. In what form should the remotely sensed data be presented? (Computer tabulations, imagery, graphical plots, computer maps etc.)____________________

9. What types of equipment are currently employed, by your organization, for remote sensing? Give operating frequencies, wavelengths, accuracies, resolution______

10. Are samples of data, obtained with your equipment, available for inclusion in our report?________Please describe and attach to this Questionnaire__________

11. Have there been any significant data interpretation problems associated with your current remote sensing techniques?________Please describe________________

12. Please give names of other users, or potential users, for remotely sensed data in your area of interest________________

13. Please provide list of technical reports or papers, published in connection with your current remote sensing program (attach to this Questionnaire).

14. In your opinion, what are the advantages and disadvantages of microwave radiometric remote sensing, from aircraft and spacecraft, over other techniques?___

15. Other comments________________

(Signature) ________________________

(Name, please print) ________________________

(Title) ________________________

(Tel. No.) ________________________

Section 3

TERRAIN SURVEY RESULTS

As stated in the preceding Section, a total of fifteen (15) replies were received from twenty-four (24) Survey Questionnaire solicitations. For ease of review, replies to the key items have been summarized in Table 3-1. These are considered to be representative of the remote sensing community since they furnish a rather wide variety of useful information.

It is worth reviewing some the key requirements listed by the respondents. Referring to Table 3-1 the following materials and phenomena are of interest to users:

Soil classification, moisture, depth and particle size.
Soil cover and plant type.
Estimates of soil evapotranspiration.
Land use patterns.
Percentage stone in land areas.
Sand and mud flat areas.
Beach erosion.
Drainage patterns.
Snow, glacier ice, lake ice and sea ice.
Fresh water quality and temperature.
Lake wave height.
Flood boundaries.
Sediments and suspended materials.
Environmental pollutants on land and in water.
Forest fires.
Crops, forests, forest burned and clear cut areas.
Vegetation cover types.
Geological features - fault lines, volcanic activity, lava flows, and extent of strip mining.

TABLE 3-1 - SUMMARY OF TERRAIN SURVEY

Questionnaire Item	Bruce J. Blanchard	Craig L. Wiegard	Saul Cooper
1. User name and address	USDA, Agric. Res. Service Chickasha, OK	USDA, Agric. Res. Service Weslaco, TX	US Army Corps of Engineers (NED) Waltham, MA
2. Materials and phenomena of interest	Soil moisture, particle size, soil depth and classification soil cover and plant type.	Land use; soil water content and estimation of evapotranspiration; crop discrimination; soil salinity.	Monitoring quality and quantity of surface water; vegetation, soil and land use parameters affecting runoff. Snow cover; effects of floods, river and coastal.
5. Required data accuracy	$\pm$ 1°K; $\pm$ 3°K acceptable over $\frac{1}{2}$ sq. mile or larger	$\geq$ 90% accuracy 0.5 - 1°K	None given.
6. Required spatial resolution	4047 sq. meters (1 acre).	30 meters.	36.8 sq. meters (400 sq. ft.)
7. Types of correlative data needed	IR surf. temps., related to each data point.	IR temps., solar radiation, Visible and reflective IR, photography.	Ground truth of hydrometeorological parameters from in situ sensors or field survey parties.
8. Form of data presentation	Imagery and computer compatible tapes.	Imagery with annotated distance and grid superimposed coord.; computer maps; digital mag. tapes.	Computer tabulations; imagery, graphical plots, computer maps.
9. Equipment currently employed	L, X and K_a-band radiometers. L and X-band radar.	L, X and K_a-band radiometers. L and X-band radar.	No imaging eqpt. Have major program in automated data collection (See Reference 5).
14a. Advantages of microwave radiometry	Expect it can sense vegetation cover and hydrologic capability of soils.	All-weather capability.	See reply under Harlan L. McKim, US Army CRREL
14b. Disadvantages of microwave	None given.	Lack of data processing that provides data in same format and resolution as visible and IR sensors.	See reply under Harlan L. McKim, US Army CRREL
15. Other comments	None given.	Should investigate microwave response with ground-based & low altitude airborne systems	Most of NED's publications refer to DCS and are probably irrelevant to this survey.
Editor's note:	Answers given are quite comprehensive and Questionnaire should be read in detail.		

TABLE 3-1 (Continued)

Questionnaire Item	Harlan L. McKim	Donald R. Wiesnet	Roger G. Barry
1. User name and address	US Army Cold Regions Res. & Engineering Laboratory Hanover, NH	NOAA Nat. Env. Sat. Service Suitland, MD	Inst. of Arctic & Alpine Research, Univ. of Colorado, Boulder, CO
2. Materials and phenomena of interest	Land and water surfaces. Land use patterns, soil moisture, water quality, intertidal habitats, sand and mud flats, eel grass, thermal pollution, snow depth and density.	Soil identification, temperature and moisture. Snow moisture, depth and density. Flood boundaries, water pollution, beach erosion. Hydrogeological-glacial, snow and ice.	Hydrogeological, geological, ecological. Vegetation cover types.
5. Required data accuracy	5 - 10°K; 15 meters nominal.	5 - 100 m, depending on application (see Attachment I to Questionnaire).	Position within 100 m.
6. Required spatial resolution	Profile resolution 5 - 10 meters. Spatial resolution 184 - 460 sq. meters	10 - 100 m, depending on application (see Attachment I to Questionnaire).	≤ 10,000 m^2 for most studies.
7. Types of correlative data needed	Soil and vegetation type. Surficial geology maps, soil moisture, water quality, temp., sediment concentrations, low altitude airborne imagery.	Streamflow; snow depth, albedo and physical properties; surface temp., soil moisture; spectral reflectance; spectral emissivity, atmospheric attenuation; lake levels.	Time overlays of snow cover and sea ice.
8. Form of data presentation	Computer maps and tabulations.	Imagery with computer tabulations, when required i.e., backup tapes for detailed analysis.	Imagery, computer maps.
9. Equipment currently employed	Have used NASA PEMIS (X-band, 0-300°K, resolution of 1219 m, from h = 1219 m).	NOAA-2 sensors: Scanning radiometer. Vert. temp. profile radiometer. Very high resolution radiometer.	None.

TABLE 3-1 (Continued)

Questionnaire Item	Harlan L. McKim	Donald R. Wiesnet	Roger G. Barry
14a. Advantages of microwave radiometry	Min., interference from atmos. haze and clouds; soil moisture and water salinity detection; oil spill detection.	Can penetrate cloud cover. Radar has good to excellent spatial resolution.	Airborne SLR is useful in mapping sea ice age distribution in presence of snow cover.
14b. Disadvantages of microwave radiometry	Cost and spatial resolution.	Theory insufficiently developed for terrain analysis. Poor resolution from satellite.	Spatial resolution of satellite radiometry is too coarse for most of our work.
15. Other comments	None given.	We want a radar in space.	Most of our research has been with visual and IR imagery. Have used some SLAR imagery of sea ice, supplied by Canadian Defence Research Board.

TABLE 3-1 (Continued)

Questionnaire Item	J.W. Jarman	A.N. Williamson	Alan E. Strong
1. User name and address	US Army Corps of Engineers Washington, DC	US Army Engineers Waterways Experiment Station Vicksburg, MS	NOAA Nat. Env. Sat. Service Suitland, MD
2. Materials and phenomena of interest	Water and related land resources.	Sediments and suspended materials; transport and deposition of materials; land use; flooding.	Water pollution - thermal and chemical. Hydrogeological - glacial, snow and ice. Mostly fresh water lake determinations: Waves, temperatures, color (Much value in multispectral sensing). Lake ice.
5. Required data accuracy	A function of use of data.	Spatial accuracy: 150 meters Spectral resolution: ± 2%.	Lake water temps.: Within 0.5°C absolute. Relative accuracy: ~ 0.25°C.
6. Required spatial resolution	Square miles.	2023 sq. meters (0.5 acre).	1 km, from satellites.
7. Types of correlative data needed	Ground observations.	Suspended material concentration (total) in mg/l. Secchi depth; water depth.	Multispectral aircraft and satellite data. Models and ground truth.
8. Form of data presentation	Various.	Computer compatible tapes and black-and-white imagery.	Imagery and computer maps.
9. Equipment currently employed	No in-house acquisition capability	ERTS-1 Multispectral Scanner; NASA 24-channel scanner; multispectral photography. Interests are primarily between, but not always restricted to 0.5 to 1.1 μm.	NOAA-2 and ERTS-1 satellite systems.
14a. Advantages of microwave radiometry	All-weather capability.	The output of microwave radiometers must be interpreted in the same manner as aerial or satellite photography. The results are, therefore, subjective and affected by the skill and background of the interpreter.	Can detect lake ice through cloud cover; important during winter months.
14b. Disadvantages of microwave radiometry	None given.	See above.	IR has resolution required for lake surface temperatures
15. Other comments	None given.	None given.	None given.

TABLE 3-1 (Continued)

Questionnaire Item	John D. Koutsandreas	Bart Hague	George W. Bailey
1. User name and address	Environmental Protection Agency, Washington, DC	Environmental Protection Agency, Boston, MA	Southeast Envir. Res. Lab., Env. Protection Agency, Athens, GA
2. Materials and phenomena of interest	Environmental pollutants on land and in water.	Point and non-point sources of pollution.	Soil identification, temp., and moisture. Snow moisture. Discrimination between crops forests and other vegetation. Discrimination between crops. Crop and forest growth stage and acreage. Assessment of forest burned and clear cut areas. Land use. Spatial distribution of crops. Type and spatial distribution of soil. Conservation practices. Drainage. Percentage stone.
5. Required data accuracy	Salinity: < 1 pt.per thousand Oil: < 0.1 mm.	± 0.1°C, ± 15 m .	± 0.5°C and ± 1% soil moisture.
6. Required spatial resolution	46 sq. meters.	Sq. ft., for water uses; acres for land use patterns.	Acres.
7. Types of correlative data needed	In situ data on pollution concentrations.	Climate; soil reports; well records; hydrological studies, topographic, surficial geol., and bed rock geol., maps.	Must establish veracity of relationships; therefore need ground truth data to establish relationship for above-listed parameters.
8. Form of data presentation	Imagery is usually most useable.	Evaluation: Computer tabulations Description: Imagery, computer maps.	Computer tabulations and computer maps.
9. Equipment currently employed	Metric cameras, IR scanners, panoramic cameras, lidar (visible and IR for air pollution).	None.	Cameras - black and white and color, IR thermal scanner, microwave and radar.
14a. Advantages of microwave radiometry	All weather. Quantitative data.	Unaffected by cloud cover; can provide temp. data; less expensive than radar.	May have unique capability to detect soil moisture content, with spatial and vertical distribution.

TABLE 3-1 (Continued)

Questionnaire Item	John D. Koutsandreas	Bart Hague	George W. Bailey
14b. Disadvantages of microwave radiometry	None given.	Less spatial resolution than radar.	None given.
15. Other comments	Interested in detecting salinity in soils. Also, need volume of oil spilled on water. In addition, inter ested in detecting acid drainage from mines and chemical effluents from industrial plants.	Interested in following: Swamps, bogs, marsh, drainage impoundments. Water pollution, turbidity, mixing zones, toxic substances (metals). Air pollution. Sewage and solid waste disposal, trenching, excavating and grading, dewatering, construction materials, soil impaction, groundwater supply, pond or lake construction, foundations, and highway construction.	Military classified information on sensors, and related technology, should be declassified, in the main, to save duplicative research by civilian sector.

TABLE 3-1 (Continued)

Questionnaire Item	G.B. Torbert and J.M. Linne	Mark F. Meier	Stanley F. Kapustka
1. User name and address	Bureau of Land Management, (BLM), Dept. of the Interior Washington, DC	US Geological Survey Tacoma, WA	US Geological Survey Portland, OR
2. Materials and phenomena of interest	All items in Questionnaire.	Snow, glacier ice.	Soil identification and moisture. Discrimination between crops, forests and other vegetation. Flood boundaries, water pollution, beach erosion, geological features and hydrogeological features.
5. Required data accuracy	Various, depending on application.	2 - 5^{o}K absolute accuracy. Position accuracy commensurate with resolution.	Various.
6. Required spatial resolution	.4 m^2 to 2.6×10^6 m^2, depending on application.	1 m^2 for ground-based radiometers. ~ 1 km^2 for aircraft. Much coarser resolution from satellites.	Use acres for water surface areas. Depends on application.
7. Types of correlative data needed	Water flow, temperature, salinity, pH and turbidity. Plan to obtain these and other data with Data Collection Platforms.	Snow temp., sky brightness temp. Snow wetness, density, grain size etc.; substrate properties.	Need accurate ground data for calibration and verification for any parameter to be identified or measured.
8. Form of data presentation	To be defined later by BLM and winner of contract study.	Computer tabulations, imagery, graphical plots, computer maps.	Computer tabulations, imagery, graphical plots, computer maps.
9. Equipment currently employed	ERTS-1 Multispectral Scanner; 9 X 9 in. B&W and color photog; 35 mm color photog.; IR scanner and radar.	Have used 3 mm, 8 mm, 1.55 cm 2.8 cm, 6 cm, 11 cm and 21 cm radiometers. Accuracies ~ 1 - 10^{o}K; resolution 20 cm - 25 km	ERTS-1 Data Collection Platform used for stream flow data. Computer-compatible tapes from ERTS to compute water surface areas.

TABLE 3-1 (Continued)

Questionnaire Item	G.B. Torbert and J.M. Linne	Mark F. Meier	Stanley F. Kapustka
14a. Advantages of microwave radiometry	Capable of penetrating cloud cover and operating day or night.	All-weather system. Senses all significant snow properties: Wetness, density, thickness, substrate properties, etc.	Not knowledgeable about this technique.
14b. Disadvantages of microwave radiometry	Good spatial resolution difficult to achieve from satellites.	None given.	None given.
15. Other comments	Interested in monitoring coal-stripping operations. Would like means for examining forest understory, since this is fuel source for forest fires.	None given.	None given.

Most of the users need temperature data. The required absolute accuracy lies in the range 0.1 to 10°K; however, accuracies in the range 0.1 to 2°K are the most popular. Other accuracy requirements are: Salinity - < 1 part per thousand; Oil spills - < 0.1 mm; Soil moisture - ± 1%.

Spatial resolution requirements fall in the range .4 m^2 to 2.6×10^6 m^2, with the median value lying at approximately 4047 sq. meters. One respondent (U.S. Army CRREL) needs a profile resolution of 5 to 10 m.

A wide variety of correlative data appear necessary for remote sensing data interpretations. The following requirements were listed in response to Item 7 in the Questionnaire:

Surface temperatures (IR or other)
Solar radiation flux
Multispectral data
Visible and reflective IR data
Spectral emissivity and reflectance
Photographic data (black-and-white and color)
Soil type, moisture, salinity and density
Vegetation type and height
Surficial geological maps
Topographic maps
Bedrock geological data
Water quality and depth
Water pollution concentration
Streamflow
Suspended material concentration
Water salinity
Water pH
Snow depth, wetness, density and grain size.
Time overlays of snow cover and sea ice
Sky brightness temperatures
Atmospheric attenuation
Microwave

Clearly, collection of the above data would require a formidable array of instruments and equipment. Furthermore, if more than one site were involved in a given sensing application, which is very likely, certain portions of this group of instruments would have to be multiplied by the number of sites. This problem would, of course, be somewhat mitigated by the existence of portions of the needed instrumentation in the user's inventory.

With reference to the required form of data presentation, most users specified a need for imagery. Most of them require computer compatible magnetic tapes from which computer tabulations, maps and plots can be generated for further analysis of imaged data.

Many of the users have employed microwave radiometric sensors in their work; some have used radar. Many are also exploiting the ERTS-1 Multi-Spectral Scanner system. This includes, of course, the USGS and NOAA. The latter Agency is also using its visible and infrared radiometers in the NOAA-2 Satellite. Black-and-white and color photography are widely used by the Department of the Interior and the Environmental Protection Agency. It is assumed that false color infrared photography is employed by some users; however, there was no mention of this technique in the responses.

It was noted, during the survey, that some users were not very familiar with the utility of microwave radiometric sensing. During the course of several interviews, it was necessary to give lengthy tutorials on this technique. It would appear that an extensive educational process may be required before widespread use of microwave radiometry can be anticipated. The impression gained during the survey was that, unless there is broader dissemination of information on the capabilities of microwave radiometry, widespread application of this remote sensing technique is unlikely to occur for some time.

An excellent beginning in this direction would be an annotated and tutorial bibliography on microwave radiometry, similar to that prepared by M.L. Bryan [6] on radar. Dr. Bryan's work is quite impressive and his approach warrants some attention.

During the course of the survey, a considerable quantity of technical material was furnished by users and research scientists on various remote sensing techniques. A particularly interesting collection was provided on microwave radiometry by Dr. T.J. Schmugge of NASA Goddard Space Flight Center. Another, even more comprehensive, collection of reports on remote sensing in the visible spectrum was furnished by Professor L.F. Silva of the Laboratory for Applications of Remote Sensing, Purdue University. All of this material is listed in the Bibliography.

Section 4

ADVANTAGES AND DISADVANTAGES OF MICROWAVES

Survey Questionnaire Item 14, concerning the advantages and disadvantages of microwave radiometry, evoked some interesting replies. The advantages cited were as follows:

1. All-weather, day or night, sensing capability.
2. Useful for detection of soil moisture, water salinity and oil spills.
3. Capable of providing surface temperature data.
4. Capable of detecting lake ice through cloud cover.
5. Has detected terrain under snow and can provide information on snow wetness, density and thickness.
6. Less expensive than radar (no transmitter).

The disadvantages of microwave radiometry were less frequently mentioned. Comments received were as follows:

1. Inadequate spatial resolution from satellite altitudes.
2. Theory insufficiently developed for terrain analysis.
3. Data interpretation tends to be subjective and is, partly, due to high skill and technical background required of the interpreter.
4. Equipment is more expensive than sensors in visible region of the spectrum.

Several favorable comments were made with respect to side-looking radar (SLR) [7] in connection with the above remarks. These include the following:

1. Good spatial resolution from satellite altitudes.
2. Useful in mapping sea ice age distribution through snow cover.
3. All-weather capability.

It is worth elaborating somewhat on the above user comments, in terms of the various naturally occurring and man-made features. This discussion will be divided into two parts: Airborne and Space microwave systems, respectively.

4.1 AIRBORNE MICROWAVE SYSTEMS

Both microwave radiometry and side-looking radar (SLR) can detect land-water boundaries with considerable ease. This is due to the strong contrast in emissive and reflective properties of land and water. Accordingly, these systems will clearly delineate flood boundaries, stream channels, lakes, lagoons, barrier islands, tidal creeks and inlets, tidal marshes, stream terraces and flood plains, and drainage patterns.

In addition, both types of sensors are capable of detecting various water-associated man-made features such as harbors, ship channels, piers, ships, bridges, seawalls, and water-treatment sites.

Further, these systems can furnish imagery for the location and identification of other man-made features such as urban and residential areas, parks, sports arenas, industrial complexes, airports, sewage-disposal plants, highways, railroads, large high tension towers, tank farms, quarries, and cemeteries.

All of the above features can be detected in a variety of atmospheric conditions and in the absence of sunlight. The degree to which microwave sensors can penetrate various cloud, rain and precipitating snow conditions is, of course, dependent on operating frequency and, in the case of radar, on transmitter power.

In addition to the above features, Reference [1] report showed that a microwave radiometer can discriminate between the following materials:

Dry and moist soils versus weed-covered loam
Limestone and pumice versus weed-covered loam
Wheat, oats and alfalfa versus weed-covered loam
Dry and wet snow, and ice versus stoney loam
Forest fires versus forested areas.

Terrain imagery obtained with the NASA Goddard Space Flight Center (GSFC) airborne Electrically Scanning Microwave Radiometer (ESMR) is quite impressive 8,9 . The false color strip-map presentations cover the brightness temperature range from $170^{o}K$ to $280^{o}K$ and resemble the false color ERTS-1 data. Such presentations, when correlated with topographic, hydrogeologic, and geologic maps, can be very useful in data interpretation. It will be recalled that most of the respondents to the Survey Questionnaire specified a need for imagery, for ready examination of remote sensing data in the early stages of data analysis. Thus, to be successful, microwave systems must be capable of furnishing suitable imagery. This information must, of course, be adjustable in scale and geometrically correctable to permit ready correlation with topographic maps.

The disadvantages of airborne microwave systems were cited, in part, at the beginning of this Section. Reference was made there to inadequate spatial resolution, with microwave radiometers, from satellite altitudes. This comment could also apply to airborne radiometric systems, if the required resolution is of a high order, the radiometer operating frequency is low, and the aircraft is at a high altitude. For example, consider the following conditions:

Radiometer operating frequency:	1.4 GHz (λ = 21 cm)
Antenna aperture:	1.82 meters
Operating altitude:	3048 meters

At nadir the 3-db antenna beamspot diameter would be close to 427 meters; at a 45-degree incidence angle it would be 854 meters (double major-axis of ellipse). Thus, the spatial resolution available with the system would range from approximately 0.45 km to 0.9 km. The swath width, for a ± 45-degree raster scan would be approximately 7 km. If a factor-of-two improvement in spatial resolution were desired, the altitude would have to be lowered to 1524 meters; thus, the available resolution would be 214 to 427 meters, over the above angular range, and the swath width would reduce to 3.5 km.

The above example illustrates the difficulty involved in realizing high spatial resolution with microwave radiometric sensors. Of course, many terrain features do not require resolution of 214 to 427 meters, although the median value specified by the users (Section 3) was approximately 4047 sq. meters. Now, if one were to consider operation at S-band (2.7 GHz), there would be a factor-of-two improvement in spatial resolution, with the same antenna aperture and operating altitudes. Thus, an S-band system would come close to satisfying the 1-acre resolution requirement, at an altitude of 1524 meters.

Airborne side-looking radar (SLR) is capable of considerably higher spatial resolution. For example, the AN/APQ-102A (X-band) system has a resolution of 15 meters. Since this is a focused synthetic aperture radar, the resolution is independent of operating altitude. In fairness to microwave radiometric systems, however, it should be stated that an X-band radiometer, operating with a 6-foot-aperture antenna would have a resolution of 29 to 58 meters, over a ± 45-degree scan angle, from an altitude of 1524 meters.

A disadvantage of radar is that it cannot measure temperatures or salinities. SLR is also a good deal more expensive than a microwave radiometer operating at the same frequency.

4.2 SATELLITE MICROWAVE SYSTEMS

The basic difference between airborne and satellite operation is the much greater distance from the sensor to the earth's surface. At an altitude of 926 km, this distance is approximately 600 times greater than the above-mentioned 1524 meter altitude. Accordingly, the above radiometer resolutions will be degraded by this factor, if the antenna aperture remains fixed.

If, however, the antenna aperture were increased to 100 meters (328 feet), this factor would be reduced to about 11. At S-band, a radiometer would, then, have a resolution of 1.85 to 3.7 km over the ± 45-degree scan angle. For the L-band radiometer, this would degrade to 3.7 to 7.4 meters. These resolutions would make microwave radiometers quite attractive for remote sensing from space.

In contrast to the above, a focused SLR will retain its resolution capability regardless of altitude. Thus, the afore-mentioned SLR system will demonstrate a resolution of 15 meters at a satellite altitude of 926 km. This should be of considerable significance to the remote sensing community, particularly since an

X-band SLR will be capable of furnishing a variety of useful data under most weather conditions. It would, therefore, appear that a focused SLR could fulfill an important role in remote sensing of terrain-related parameters from spacecraft altitudes.

4.3 SOPHISTICATION OF MICROWAVE SENSORS OVER OTHER TECHNIQUES

Microwave sensors possess an inherent sophistication, relative to sensors in the visible and infrared regions of the spectrum, due to the decreasing attenuation in physical matter with increasing wavelength. Thus, depending upon wavelength, the atmosphere and terrestrial materials can be fairly transparent or quite opaque.

A clear atmosphere is relatively transparent at, both, long and short wavelengths through the visible region of the spectrum. However, the presence of condensed water vapor causes heavy attenuation of electromagnetic energy, beginning with the higher millimeter-wave region. At infrared and optical wavelengths, the attenuation due to clouds is so great that even thin cloud layers are essentially opaque. Thus, in the presence of clouds and heavy haze the earth is masked from the view of satellite sensors operating at infrared and optical wavelengths. Such is not the case in the microwave region of the spectrum. Here, with the exception of the weak water vapor absorption peak at 22 GHz, clouds are relatively transparent from 1 GHz to about 40 GHz, although the attenuation increases progressively with frequency. Therefore, microwave satellite sensors have an inherent advantage over infrared and optical sensors, due to their ability to "see" through a cloudy atmosphere.

Similar statements may be made concerning the attenuation of electromagnetic energy in dielectrics, such as solid terrestrial materials and water. Due to the high attenuation in these materials, in the infrared and optical region, they are opaque at these wavelengths. However, depending on the value of the complex dielectric permittivity, at a given frequency, microwave energy can penetrate these materials to some degree. Thus, microwaves are not confined to surface effects; it is possible to sense energy emanating from some depth beneath the surface of a dielectric material. This has important ramifications in remote sensing, for it permits detection and measurement of such items as subsurface moisture in soils; moisture content of snow; ice and soils through snow cover; and terrain and water through foliage. Examples of these capabilities are given in References [3], [8], [4] and [3] respectively.

Another useful characteristic of microwaves is that of antenna polarization. An antenna can be horizontally polarized (E vector perpendicular to the plane of incidence), vertically polarized (E vector parallel to the plane of incidence) or circularly polarized, which represents a combination of horizontal and vertical polarizations. An antenna designed to receive energy at a given polarization will essentially reject most of the energy from the other polarization component.

Both microwave radiometry and radar, when operating with linearly polarized antennas, show markedly different results for horizontal and vertical polarizations. A good example of these responses is shown in Figure 4-1 wherein theoretical brightness temperatures are shown at a frequency of 2.5 GHz, for two wind velocities [9]. During the course of the referenced study, it was found that use of the vertical component of polarization results in smaller errors, when deriving ocean temperatures from brightness temperatures, than is the case with horizontal polarization. This is because the latter polarization is somewhat more sensitive to surface roughness. Subsequent studies [10] show that the sensitivity of the horizontal component of polarization to surface roughness forms the basis for a remote sensing technique that will furnish information on ocean surface wind velocity with a maximum error of ± 1.5 m/s under a relatively broad range of environmental conditions, with an error-free radiometer.

Radar has been used fairly extensively for indirect measurement of ocean surface wind velocities [11]. In the referenced work, both horizontal and vertical polarizations were employed. Results . . ." indicate that the scatterometer response is essentially proportional to the square of windspeed for vertical polarization".

The above comments on polarization effects indicate an added sophistication inherent in microwave sensors, thus enhancing their value for remote sensing.

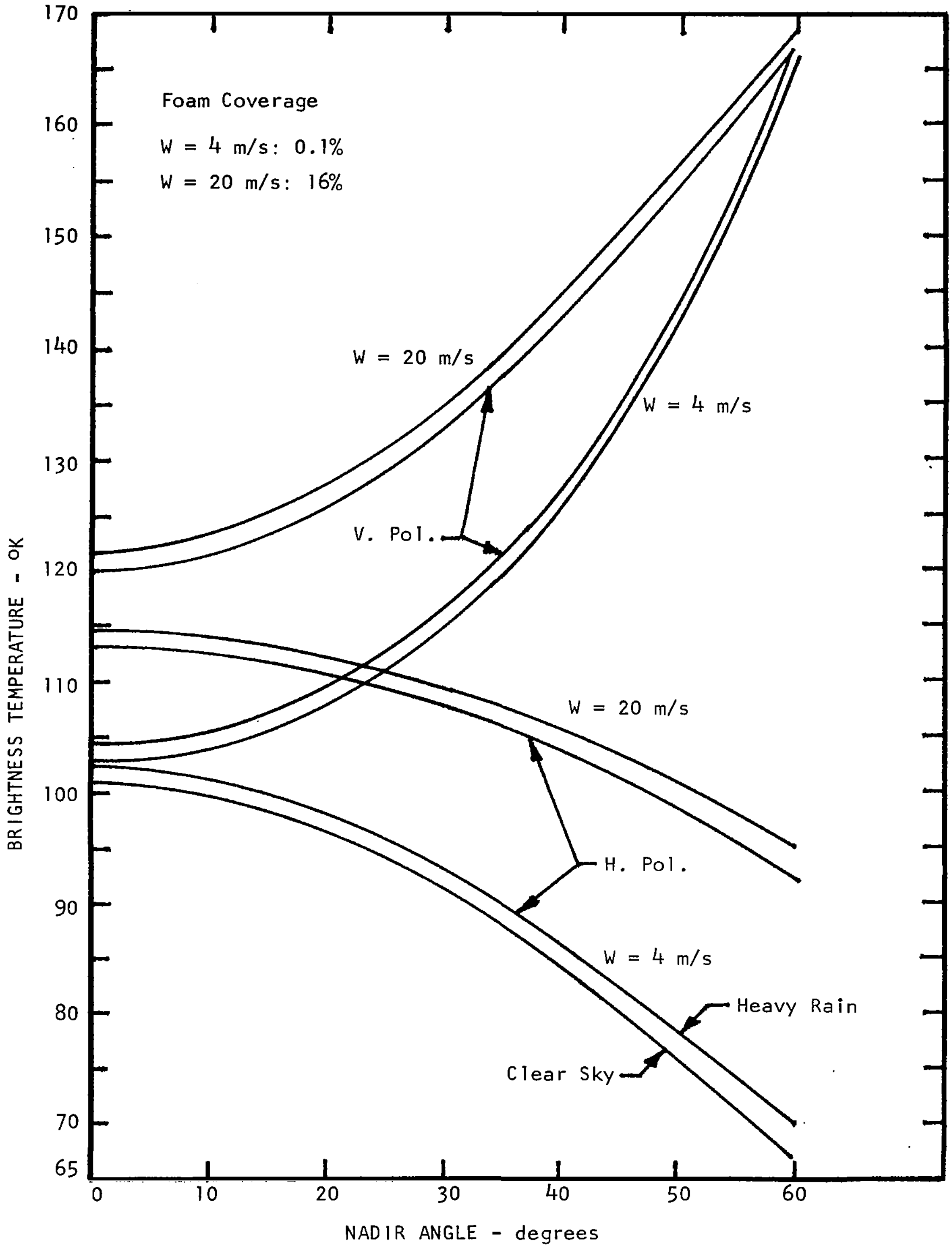

Figure 4-1 - Brightness Temperatures of Rough, Foam-Covered Ocean Surfaces (2.5 GHz, T = 284°K, S = 33 °/oo, W = 4 and 20 m/s, Clear Sky and Heavy Rain)

Section 5

DATA ANALYSIS PROBLEMS WITH MICROWAVES COMPARED WITH OTHER TECHNIQUES

Proper interpretation of data from a remote sensing system requires that the user be knowledgeable about the energy-matter interactions taking place between,

1. The vegetation, soil, snow, ice, water or other material on the earth's surface,

and 2. The energy that is reflected, absorbed, transmitted, scattered or emitted by those materials.

Knowledge of these energy-matter interactions permits the spectral characteristics of the materials to be predicted and the remote sensor data to be accurately interpreted.

The above statement appears in slightly different language in a technical note by Hoffer [12]. Hoffer goes on to make the following statement:

> "In remote sensing research involving vegetation, we are frequently interested in one or more of three problem areas:
>
> 1. To delineate, identify, and map various species (i.e. floristic mapping).
> 2. To delineate, identify, and map vegetative groupings having different physical characteristics (i.e. physiognomic mapping).
> 3. To detect, identify, and map various types of vegetative stress conditions (e.g. stress caused by diseases, insects, lack of available soil moisture, fertility, pollutants in the air or water, etc.)."

Similar comments can be made about other materials and phenomena. However, accurate analysis of remotely sensed data is dependent on a considerable store of knowledge relative to the spectral characteristics of given materials and phenomena.

Such characteristics are reasonably well known in the visible and infrared regions, due to the rapid development of components and remote sensing techniques. The success of the ERTS-1 system, and similar airborne and ground-based systems, substantiates this statement.

A variety of sophisticated processing and computer analysis techniques, including pattern recognition, have been developed for semi-automated analysis of data collected by multispectral sensors, by such institutions as the Environmental Research Institute of Michigan (ERIM) and the Laboratory for Applications of Remote Sensing (LARS) at Purdue University. These techniques have permitted rapid and accurate analysis of large amounts of data recorded by, both, the ERTS-1 system and airborne visible and infrared sensors.

Unfortunately, similar claims cannot be made for microwave systems, due to the somewhat slower development of, both, these systems and related data interpretation techniques. This lag has been, partly, due to insufficient emphasis on ground-based measurements, wherein the radiometric and radar characteristics of materials could have been obtained under known conditions.

During the latter half of the 1960's there was a great rush, by several groups, into airborne microwave systems - long before any comprehensive knowledge was available on the characteristics of materials and phenomena at various frequencies in this region of the spectrum. As a result, a great deal of conjecture arose as to the meaning of much of the data collected with these systems. These controversies persist to this day, although at a diminished level. This is due to an increased awareness, in recent years, of the need for better information on the microwave response to various materials and phenomena. Work by many researchers within NASA, NOAA, the U.S. Naval Research Laboratory, the Environmental Research Institute of Michigan, Ohio State University, University of Kansas and several industrial research firms has contributed markedly to enhanced knowledge in this area. However, a great deal remains to be accomplished before microwave sensor data can be analyzed with the precision and efficiency of information collected by visible and infrared sensors. This view is reflected in some of the user responses appearing in Section 3.

As stated in Section 4, most of the users, responding to the Survey Questionnaire, specified a need for imagery to facilitate data interpretation. It is evident, from a review of Reference [8] that false color imagery is of considerable value in the analysis of microwave radiometric data. Accordingly, it would seem appropriate to utilize this form of presentation with any scanning system. However, such displays should be geometrically corrected to facilitate comparison with topographic maps. Computer maps are also very useful in data interpretation, as shown in many reports by ERIM and LARS. For ease of examination, however, individual maps should be limited to a maximum of four or five symbols.

The five most important problems in the analysis of remotely sensed microwave radiometric data are considered to be as follows:

1. Achievement of accurate, absolute temperature calibration of the radiometer.
2. Elimination, or compensation for, the tendency of apparent temperatures, at the center of a transverse scan, to be higher or lower than those at the edges of the scan, depending on whether a vertical or horizontally polarized antenna is employed, respectively.
3. Compensation for radiations received via the antenna sidelobes.
4. Elimination of the effects of reflected solar radiation from specular surfaces such as water.
5. Development of automated data analysis techniques, similar to those used with optical sensors.

5.1 RADIOMETER CALIBRATION

Various approaches are used in radiometer calibration. The important elements of a sound method are summarized below:

1. The calibration circuit and the RF portion of the radiometer should be housed in a well-insulated temperature-controlled enclosure, to reduce to a minimum fluctuations, due to temperature changes, in reradiation from lossy components in the calibration circuit, and in output level from the calibration source. Good temperature stability also minimizes voltage gain fluctuations in solid-state RF amplifiers.

2. The noise levels of the calibration circuit should be determined indirectly by measuring the response of the radiometer to accurately known input noise temperatures, furnished by a stable external noise source. If possible, the error in the external level-setting attenuator should not exceed 0.05 db.

3. The radiometer amplifiers and other critical circuits should be powered by highly stable regulated power supplies which, in turn, should be supplied with clean, stable primary power.

4. The radiometer RF head should be thoroughly shielded against electromagnetic interference and all RF cables running to and from the radiometer should be double-shielded.

5. During normal operation, the radiometer should be calibrated frequently, consistent with the long-term gain drift of the receiver amplifiers.

If the above basic rules are observed, data analysis will be greatly facilitated by the elimination of shifts in absolute apparent temperatures measured by the radiometer. Some early radiometer measurement programs have suffered because of insufficient attention to these important items.

5.2 NON-UNIFORM APPARENT TEMPERATURES ACROSS SCAN

This problem occurs mainly when a radiometer is covering a wide angular scan (typically ± 45 degrees) over specular or near-specular materials. Referring to Figure 4-1, it will be observed that the vertically polarized brightness temperatures of ocean water increase markedly from a nadir angle of zero degrees to an angle of 45 degrees. In the case of the horizontal component of polarization, the opposite is true. Similar brightness temperature responses are obtained for fresh water and other specular and near-specular materials.

There is no basic objection to these characteristics when data is presented in the form of plots or when comparisons are made between various materials at the same nadir angle. The problem arises in false color imagery, since most apparent temperatures at, and near, the center of the scan are presented in different colors than those near the edges. Thus, material identification and classification can be difficult with this type of display.

Three solutions seem possible to this problem. The first and easiest one is to limit the angular scan, whenever possible, to about ± 15 degrees. This has a disadvantage in that the swath width will be rather narrow. In addition, angular effects will be minimized in the data; this may present problems where the angular dependence is important to the user. The second solution is to introduce a compensation to the data for the angular curvature, over the scan width, by observing typical curvatures over a variety of terrain. This correction would only be applied to false color imagery. This type of angular rectification should markedly increase the value of this form of data presentation. The third solution is, perhaps, the best; it involves the use of a conical scan, wherein the angle of incidence of the antenna beam, at the terrain surface, is constant over the swath width. Of course, this method may be difficult to implement in electronically scanned phased array antennas, but it represents a reasonable solution to the problem of non-uniform apparent temperatures across the antenna scan.

5.3 COMPENSATION FOR RADIATIONS RECEIVED VIA THE ANTENNA SIDELOBES

Radiations received via the antenna sidelobes and backlobes tend to raise the apparent temperatures sensed by a terrain-scanning radiometer. Depending on the actual sidelobe levels and observed material, the increase in apparent temperatures due to this effect can be as great as $4 - 5^{o}K$. To make matters worse, the effect tends to be a function of scan angle because, in the case of a horizontally polarized antenna, <u>all</u> the high antenna sidelobes are receiving energy from the surface at the center of the scan where the radiated energy is highest (for a homogeneous material) whereas most of the sidelobes are receiving lower level energy at the end of the scan. The opposite effect applies to a vertically polarized antenna. Thus, a signal modulation takes place during the antenna scan. For a ± 45-degree scan angle, this modulation can range from 0 to $4 - 5^{o}K$, depending on actual sidelobe levels.

This problem can be eliminated to some extent by a technique which, in effect, subtracts the energy received by the sidelobes from the total energy received by the antenna. A method for this is described in Reference [1] report. One of the problems inherent in any such technique is the considerable amount of computer processing time required to perform the corrections. Thus, certain approximations are necessary to ensure economic data reduction.

5.4 EFFECTS OF SOLAR RADIATION

This problem arises principally at frequencies below approximately 10 GHz, where solar radiation flux is relatively high, and only when a microwave radiometer is viewing highly reflective surfaces, such as water, in the direction of the sun. Reference [13] provides an analysis of this effect, over ocean surfaces, at a frequency of 2.5 GHz. The results show that, depending on the degree of ocean surface roughness, the reflected solar brightness temperature lies in the range 2.9°K to 11.0°K, in the specular direction i.e., in the main lobe of the antenna. Such "interference" would cause considerable problems in data analysis, if the higher brightness temperatures were not eliminated during data reduction. However, the problem would not exist if the solar radiation were scattered only in the direction of the antenna sidelobes. Since the average level of this portion of the antenna pattern is typically about - 20 db, with respect to main lobe peak, the above reflected solar radiation levels would be reduced by a factor of 100. Thus, solar interference would be negligible under these conditions.

The most practical way to eliminate the effects of solar radiation, scattered into the main lobe of the antenna, is to take into account the direction of the radiometer flight path, sun position and sun elevation angle during reduction of low frequency radiometer data.

5.5 AUTOMATED DATA ANALYSIS TECHNIQUES

This problem is considered to be one of the most difficult of all the problems cited at the beginning of this Section. This is partly due to the fact that microwave remote sensing is, to some extent, still in the research stage. However, this situation is expected to change during the next 2 - 3 years, with extensive operational applications developing during this period. The Nimbus 5 Electrically Scanning Microwave Radiometer (ESMR) [14] represents, perhaps, the beginning of the operational phase of, both, microwave radiometry and radar in space.

Automated data analysis is very important where large quantities of airborne or satellite data are concerned. Considerable advances have been made in this area, with optical sensors, at ERIM and LARS. D.A. Landgrebe [15] has presented a valuable summary on this topic. The referenced work furnishes an extensive bibliography on machine processing, classification and analysis of remotely sensed data. Such information can form the basis for automated analysis of microwave data; it would be wise to exploit the techniques described in the above work and associated references for this purpose.

Section 6

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